# THE UPPER RED BEDS OF THE BLACK HILLS.

CONTENTS.



## INTRODUCTION.

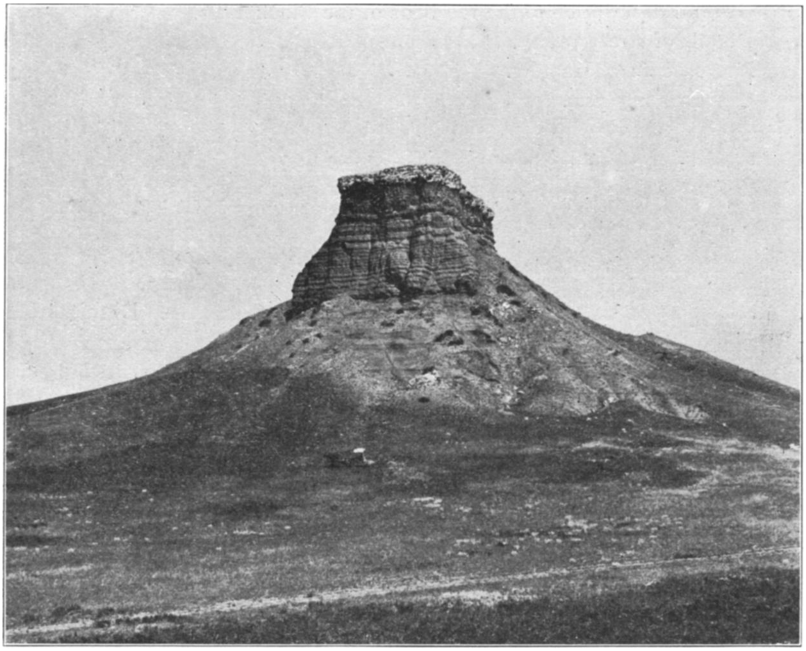
THIS paper describes the upper red beds of the Black hills and inquires into the origin of their color.

The red beds of the Black hills are composed of from five to six hundred feet of red sandstones and shales with gypsum in the upper part and a bed of limestone toward the base. This limestone enables a threefold division of the rocks.[1] The Opeche formation at the base of the series consists of a hundred feet of unfossiliferous red shaly sandstones. These lower red beds lie apparently conformably upon vari-colored calcareous sandstones of Carboniferous age, the line of division being an abrupt change in color. Separating the upper and lower red beds, and lying conformably between them, is the Minnekahta limestone, which is purplish-gray in color, about forty feet thick, persistent in its occurrence, and contains Permian fossils. The upper red beds average four hundred feet in thickness, and are composed of unfossiliferous red sandy shales and interbedded gypsum unconformably overlain by more somber-colored rocks of Jurassic age. These upper red beds, named the Spearfish formation, are the subject of this paper.

[1] N. H. DARTON, "Geology and Water Resources of the Southern Black Hills," *Twenty-first Annual Report U. S. Geological Survey*, Part IV (1901), pp. 513–19.

DESCRIPTION.

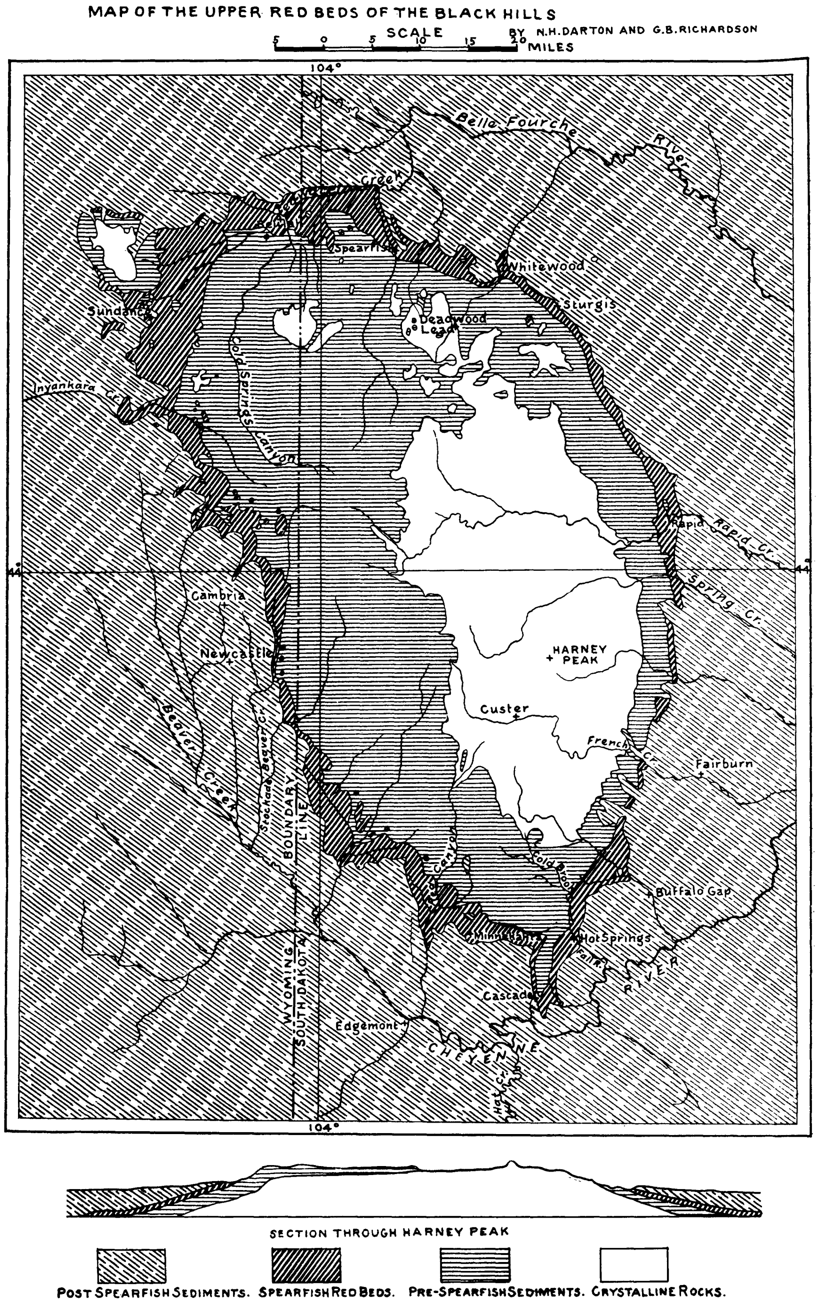
*General description.*— The accompanying map shows the Spearfish formation girdling the Black hills in a crude ellipse, one axis of which is about eighty miles and the other forty. The width of outcrop varies considerably, but averages two miles. The greatest areal extent is in the vicinity of Sundance, where the formation is eight miles wide; near Cascade Springs the



Red Butte, northeast of Cambria, Wyoming. Spearfish red beds capped by 30-foot bed of gypsum.

width, because of the steep dip there, diminishes to less than a thousand feet.

Structurally these rocks conform to the contiguous sedimentary formations by dipping on all sides from the central mass of the Black hills. This general dome structure, however, is varied by subsidiary folding. At the inner limit of the upper red beds, toward the center of the hills, the underlying purple limestone slopes upward, and the line of contact, where the softer red


MAP OF THE UPPER RED BEDS OF THE BLACK HILLS
SCALE
5 0 5 10 15 20
MILES
BY N.H. DARTON AND G.B. RICHARDSON
104°
44°
Belle Fourche River
Creek
Spearfish
Whitewood
Sturgis
Sundance
Deadwood
Lead
Inyankara Cr.
Cold Springs Canyon
Rapid
Rapid Cr.
Spring Cr.
Cambria
Newcastle
HARNEY PEAK
Custer
French Cr.
Fairburn
Beaver Creek
Stockade Beaver Cr.
BOUNDARY LINE
Canyon
Cold Brook
Buffalo Gap
Minnekahta
Hot Springs
Cascade
RIVER
WYOMING
SOUTH DAKOTA
Edgemont
CHEYENNE
Hat Cr.
SECTION THROUGH HARNEY PEAK
POST SPEARFISH SEDIMENTS.
SPEARFISH RED BEDS.
PRE-SPEARFISH SEDIMENTS.
CRYSTALLINE ROCKS.

rocks have been eroded from the surface of the limestone, is extremely irregular. The outer limit of the formation is emphasized by an escarpment formed by Jurassic and Cretaceous sandstones.

Streams coming from the high central area of the Black hills generally flow directly across the red beds, yet occasional creeks, like Red Water in the vicinity of Beulah, flow for some distance parallel to the strike of the red rocks before leaving them. The divides, however, are low and the general appearance of the Spearfish formation is that of a valley. This red valley is very conspicuous. No timber and very little vegetation are supported by the underlying rocks. Erosion has cut gullies in the shales and has exposed prominent gypsum-capped buttes, while the color contrasts of the rich red rocks and pure white gypsum form striking effects.

*Details of stratigraphy.*—The stratigraphy of the Spearfish formation is shown in detail by the following:

COLUMNAR SECTIONS.

(The heavy lines mark respectively the upper and lower contacts of the Spearfish red beds.)

I. ONE MILE UP COLD BROOK FROM HOT SPRINGS.

| | Feet. | Inches. |
|---|---|---|
| Upper contact covered. | | |
| Gypsum | 10 | |
| Red sandy shale | 3 | |
| Massive white gypsum | 3 | |
| Fine red shale | 15 | |
| White gypsum | .. | 9 |
| Red clayey sandstone | 8 | |
| White gypsum | .. | 8 |
| Red clayey sandstone | 15 | |
| Massive mottled gypsum (red sandy clay admixture) | 35 | |
| Red sandy shale with interlacing veins of gypsum 1 inch to $\frac{1}{16}$ inch thick | 3 | |
| Massive white gypsum | 3 | |
| Green-drab shale | 1 | 3 |
| Chocolate-brown hackley shale | 5 | |
| White gypsum | 4 | |
| Hard light-red clayey sandstone | .. | 8 |
| Green shale | .. | ¼ |
| Hackly brown sandy shale with a 3-inch streak of green clay | 15 | |

| | Feet. | Inches. |
|---|---|---|
| Covered to lower contact. | | |
| At contact red, clayey sandstone with minute specks of glistening quartz. | | |
| Purple limestone (Permian). | | |

II. THREE-FOURTHS OF A MILE UP COLD BROOK FROM HOT SPRINGS.

| | Feet. | Inches. |
|---|---|---|
| Massive buff sandstone (Jurassic). | | |
| Rather coarse dark brick-red sandstone with few streaks of green clay - - - - - - - - - - - - - | 20+ | |
| Concealed. | | |
| Mottled gypsum (admixture of red clay) - - - - - - | 4 | |
| Reddish sands with thin green streaks - - - - - - | .. | 8 |
| White gypsum - - - - - - - - - - - - | .. | 2 |
| Rather coherent bright red sandy shale with few small green specks - - - - - - - - - - - - - | 25+ | |
| Concealed. | | |
| Red sandy clay. | | |
| (Abrupt change.) | | |
| Massive pure white gypsum - - - - - - - - - | 18 | |
| Light red clayey sandstone with network of wafer-thin gypsum veins - - - - - - - - - - - - - | 10 | |
| Massive white gypsum - - - - - - - - - - | 8 | |
| Red sandy clay - - - - - - - - - - - - | 2 | |
| Massive white gypsum - - - - - - - - - - | 20 | |
| Red sandy clay - - - - - - - - - - - - | 40+ | |
| Lower contact covered. | | |

III. HEAD OF SHEPS CANYON, EAST OF CASCADE SPRINGS.

| | Feet. | Inches. |
|---|---|---|
| Massive yellowish sandstone with few small basal pebbles of quartz (Jurassic) - - - - - - - - - - | 30–40 | |
| Erosional unconformity. | | |
| Massive chocolate-brown, sandy shale - - - - - - | 30+ | |
| Dark brown-red clayey sandstone with green clay streaks, not continuous, and thin interlacing gypsum veins - - - - | 30+ | |

IV. CANYON NORTHEAST OF CASCADE SPRINGS.

| | Feet. | Inches. |
|---|---|---|
| Alternating red sandy shales and gypsum of undetermined thickness. | | |
| Hard red clayey sandstone with green streaks - - - - - | .. | 8 |
| Red clayey sandstone with thin partings 2-inch ± of pure white gypsum - - - - - - - - - - - - - | 10 | |
| Red sandy shale - - - - - - - - - - - - | 10± | |
| Pure white massive gypsum - - - - - - - - - | 3 | 6 |

| | Feet. | Inches. |
|---|---|---|
| Purple limestone (Permian) | 30+ | |

V. ONE-HALF MILE SOUTH OF CASCADE SPRINGS.

| | Feet. | Inches. |
|---|---|---|
| Covered to upper contact. | | |
| Red shales. | | |
| White gypsum | 5 | |
| Red sandy shale | 20 | |
| White gypsum | 20 | |
| Red sandy shale | 15 | |
| White gypsum | 5 | |
| Red sandy shale | 100 | |
| Covered. | | |
| Light red sandy clay. | | |
| White gypsum | 20 | |
| Red sandy shale | 40 | |
| Mottled gypsum (white gypsum with red clay admixtures) | 20 | |
| Red sandy shale. | | |
| Gypsum | 3 | |
| Red sandy shale. | | |
| Concealed | 100± | |
| Gypsum. | | |

Purple limestone (Permian).

VI. AT CASCADE SPRINGS.

| | Feet. | Inches. |
|---|---|---|
| Upper contact covered. | | |
| Red sandy shale | 15+ | |
| Mottled gypsum (red clay admixture) | 10 | |
| Bright red sandy shale | 5 | |
| Gypsum | 2 | |
| Red sandy shale | 3 | |
| Gypsum | 10 | |
| Red sandy shale | 10 | |
| Gypsum | 20 | |
| Red sandy shale | 10 | |
| White gypsum with few thin partings of red sandy shale | 40 | |
| Red clayey sandstone | 20 | |
| Gypsum | 20 | |
| Hackly red clayey sandstone | 10 | |
| Massive white gypsum | 8 | |
| Hard red clayey sandstone | .. | 6 |
| Red sandy shale | 20 | |
| Lower contact covered. | | |

VII. ONE MILE NORTHWEST OF MINNEKAHTA.

| | | Feet. | Inches. |
|---|---|---|---|
| Jurassic | Fissile green-drab shale | 50± | |
| | Friable white sandstone | 25 | |
| Contact covered. | | | |
| Chocolate-brown clayey sandstone with patches of green clay | | 10+ | |
| Concealed. | | | |
| Light red sandy shale with some small green specks and streaks | | 10+ | |
| Chocolate-brown mudstone | | 4 | |
| Brown-red clayey sandstone with 5 ′ bed of gypsum and some green streaks | | 20 | |
| Red sandy shales with some green streaks | | 30 | |
| Light brick-red clayey sandstone with network of thin gypsum veins | | 60 | |
| Impure red-stained gypsum | | 12 | |
| Red sandy shale | | .. | 6 |
| Pure white gypsum | | .. | 2 |
| Red sandy shale | | .. | 1 |
| Green shale | | .. | ½ |
| Red sandy shale with network of gypsum veins | | 50 | |
| Massive white gypsum | | 5 | |
| Red sandy shale with network of gypsum veins | | 15 | |
| Massive white gypsum | | 20 | |
| Red sandy shale with gypsum veins | | 5 | |
| Massive white gypsum | | 3 | |
| Red sandy shale | | 6 | |
| Massive white gypsum | | 1 | |
| Red sandy shale with gypsum veins | | 10 | |
| Mottled gypsum (admixture of red clay) | | 20 | |
| Brick-red sandy shale | | 110 | |
| Purple limestone (Permian) | | 50 | |

VIII. FOUR MILES WEST OF MINNEKAHTA.

Massive, friable sandstone, red superficially; white within. (Jurassic).

Undulating contact — sharp change.

Hard chocolate-brown sandy clay.

IX. ONE-HALF MILE NORTHEAST OF X.

| | | |
|---|---|---|
| Jurassic | Massive fine-grained sandstone; superficially stained red — paler to white within | 30–40 |
| | Shale and thin-bedded drab-green sandstone | 15–20 |
| | Buff sandstone. | |
| | Massive white sandstone superficially red. | |

| | | Feet. | Inches. |
|---|---|---|---|
| | Hard chocolate-colored shale with streaks of green. | | |

X. ONE-HALF MILE EAST OF XI.

| | | Feet. | Inches. |
|---|---|---|---|
| Jurassic | Drab shale | 50 | |
| | Buff sandstone | 5 | |
| | Drab shale | | 6 |
| | Yellowish sandstone | 15 | |
| | Light red sandstone. | | |
| | Dark red shale | 40 | |
| | Red clayey sandstone with thin beds of gypsum | 25 | |

XI. ONE-HALF MILE FARTHER UP RED CANYON FROM XII.

| | | Feet. | Inches. |
|---|---|---|---|
| Jurassic | Fine white sandstone | 15+ | |
| | Drab-green fissile shale | 50 | |
| | Friable buff sandstone | 5 | |
| | Brick-red sandstone | 15 | |
| | Chocolate-brown shaly sandstone | 3 | |
| | Green sandy shale | | 3 |
| | Fissile chocolate-brown shale | 15+ | |

XII. WHERE RED CANYON LEAVES THE RED BEDS.

| | | Feet. | Inches. |
|---|---|---|---|
| Jurassic | Drab sandstone | 10 | |
| | Green shale | 8 | |
| | Drab sandstone | 1 | |
| | Dark-green shale and thin drab sandstone | 20 | |
| | Chocolate-brown shale with fine specks of glistening quartz | 10+ | |

XIII. WEST OF FANNY PEAK.

| | Feet. | Inches. |
|---|---|---|
| Red shale | 100 | |
| Gypsum | 15 | |
| Red clayey sandstone | 100 | |
| Gypsum mottled with streaks and spots of red and purple clay | 30 | |
| Red shale | 100 | |
| Gypsum | 5 | |
| Red shale with network of gypsum veins; thin-bedded at base with no gypsum and thin streaks of green clay | 80 | |
| Purple limestone (Permian) | 10+ | |

XIV. RECORD OF WELL AT CAMBRIA, WYO.

| | | Feet. | Inches. |
|---|---|---|---|
| Jurassic | Drab shale | 60 | |
| | Gray and pink shale | 4 | |

| | Feet. | Inches. |
|---|---|---|
| Gypsum | 8 | |
| Light red shale | 237 | |
| Gypsum | 7 | |
| Red shale | 58 | |
| Gypsum | 4 | |
| Red shale with some gypsum | 78 | |
| Gypsum | 12 | |
| Red shale | 88 | |
| Purple limestone (Permian) | 42 | |

XV. SEVEN MILES SOUTH OF SUNDANCE.

| | Feet. | Inches. |
|---|---|---|
| Drab sandy shales (Jurassic) | 10+ | |
| Chocolate-brown sandy shale | 10+ | |
| Streak of green clay | .. | 2 |
| Chocolate-brown sandy shale with few green streaks | 3 | |
| Green clay | | ¼ |
| Red sandy shale | 3 | |
| Green streak. | | |
| Red sandy shale | 1 | |
| Green streak. | | |
| Concealed. | | |

XVI. ONE MILE NORTHWEST OF SUNDANCE.

| | Feet. | Inches. |
|---|---|---|
| Covered to top. | | |
| Red sandy shale. | | |
| Impure gypsum | 8 | |
| Red sandy shale with network of gypsum veins | 20 | |
| Massive white gypsum | 2 | |
| Red sandy shale | 5 | |
| White gypsum | 1 | |
| (These two gypsum beds are connected by a vein of gypsum 2 inches thick with branches.) | | |
| Chocolate-brown sandy shale | 3 | |
| White gypsum | 1 | |
| Red sandy shale with small specks of green clay | 5 | |
| Concealed | | |
| Purple limestone (Permian). | | |

XVII. SEVEN AND ONE-QUARTER MILES NORTHWEST OF SUNDANCE.

| | | Feet. | Inches. |
|---|---|---|---|
| Jurassic | Fissile drab-green shales | 40 | |
| | Buff, friable sandstone | 10 | |
| | Gray-green mudstone | 6 | |
| | Thin-bedded buff clay sandstone | 3 | |

| | | Feet. | Inches. |
|---|---|---|---|
| | Red sandy clay | 20+ | |

(In places the change from red to buff sediments is abrupt and plane. In others there is an intermingling of red and buff. In one place a pocket 2 inches deep and 4 inches wide in the red clay is filled with buff sandstone and a few rounded quartz pebbles varying in size from pin-heads to peas.)

XVIII. TWO MILES NORTHWEST OF BEULAH.

| | | Feet. | Inches. |
|---|---|---|---|
| Jurassic | Massive buff sandstone | 5 | |
| | Drab shale | .. | 2 |
| | Light brown friable sandstone | 15 | |
| | Fissile green-drab shale | 60 | |
| | 12 feet from bottom 1-inch bed of marl rich in Jurassic fossils. | | |
| | White sandstone, with pebbles of smooth, rounded quartz from size of peas down | 3 | |
| | Undulating surface of contact. | | |
| | Chocolate-brown sandy shale | 20 | |
| | Gray-drab clayey sandstone | 3 | |
| | Dark brick-red sandy shale | 5 | |
| | Gray-drab clay | .. | 2 |
| | Brick-red sandy shale | 35 | |
| | Streak of green clay | .. | 2 |
| | Red sandy shale with few streaks of green | 30 | |
| | Persistent bed of green clay | .. | 6 |
| | Red sandy shale | 25 | |
| | Streak of green clay | .. | 2 |
| | Red sandy shale | 4 | |
| | Green clay | .. | 5 |
| | Red sandy shale | 10 | |
| | Green clay | .. | 1 |
| | Red sandy shale | 15 | |
| | Green clay | .. | 2 |
| | Red sandy shale, occasional streaks of green clay | 50 | |
| | Mottled gypsum (red clay admixture) | 10 | |
| | Red sandy shale. | | |
| | Concealed. | | |
| | Red sandy shale. | | |
| | Massive white gypsum | 4 | |
| | Red sandy shale | 10 | |
| | White gypsum | 2 | |
| | Red sandy shale with veins of gypsum | 15 | |
| | Bedded gypsum. | | |

| | Feet. | Inches |
|---|---|---|
| Purple limestone (Permian). | | |

XIX. NORTHEAST OF SPEARFISH; VALLEY NEXT EAST OF LOOKOUT PEAK.

| | Feet. | Inches |
|---|---|---|
| Green shale (Jurassic) | 10+ | |
| Massive white gypsum | 2 | |
| Clayey sandstone | 12 | |
| Massive white gypsum | 20 | |
| Red sandy shale with few green streaks | 50 | |
| Gypsum | .. | 2 |
| Red sandy shale | .. | ½ |
| Green clay | .. | ½ |
| Chocolate-brown sandy shale, few gypsum veins | 20 | |
| Green clay | .. | 1 |
| Red sandy shale | 2 | |
| Gypsum | .. | 2 |
| Red sandy shale | 8 | |
| More massive sandy shale | .. | 3 |
| Chocolate-brown sandy shale with streaks of green | 1 | |
| Thin-bedded red sandy shale with specks of green | 10 | |
| Chocolate-brown sandy shale with network of gypsum veins paper-thick to 4 inches. | | |
| Covered. | | |

XX. ONE AND ONE-HALF MILE WEST OF WHITEWOOD.

Section generally covered. Impure gypsum exposed toward the middle of red clays. Uniform dips of 28° and upper and lower contacts give thickness here of 450 feet for the Spearfish red beds.

These sections show that the upper red beds of the Black hills consist of about four hundred feet of red sandy shales with interstratified beds of gypsum. The shales are generally homogeneous in color, composition, and texture, but subordinate variations are caused by small green streaks and spots. The gypsum beds are irregularly distributed in lenses throughout the formation. Adjacent to the beds of gypsum frequently the red shales are traversed by interlacing gypsum veins. No fossils have been found in the Spearfish formation.

The red beds are characteristically red, the shade varying from chocolate-brown and dark red to light red; the usual tint is a uniform dark brick-red. The unaided eye sees in a hand

specimen a fine-textured arenaceous red shale, with occasional minute glistening particles of quartz and muscovite. The rock crumbles between the fingers to a fine powder, which with water can be readily molded; breathed upon, it gives the characteristic clay odor. The rock has no pronounced structure. It is coherent, yet easily friable, and breaks unevenly, with a tendency to a hackly fracture. Bedding planes are feebly developed and usually cannot be distinguished. Occasionally, though, when sand admixture becomes so prominent as to produce a clayey sandstone, thin flaky bedding planes become distinct.

Streaks and spots of green in the midst of the red shales form local variations. The green streaks seldom are continuous, but occur irregularly, often with uneven and wavy surfaces of contact with the red rocks. In places the green streaks follow small joint planes. The size of the streaks varies from a small fraction of an inch to three or four inches in thickness. The green spots are irregularly distributed and roughly spheroidal in shape; usually of about the diameter of a pin-head, they sometimes reach half an inch in diameter. In composition the green differs from the red shale by being poorer in iron and having a higher ratio of ferrous oxide. An analysis of adjacent green and red shale gave:

| Green Shale. | | Red Shale. | |
|---|---|---|---|
| $Fe_2O_3$ - - | 1.85 per cent. | $Fe_2O_3$ - - | 4.61 per cent. |
| FeO - - - | 1.04 " | FeO - - - | 1.24 " |

Beds of gypsum occur at different horizons throughout the extent of the Spearfish formation, the greatest development being toward the middle of the series. Longitudinally no individual bed can be traced far. The thickness of the gypsum varies from a fraction of an inch to a maximum of about forty feet. Generally the gypsum is remarkably pure and the color a clear white. Occasionally admixtures of red clay produce a mottled appearance.

The following is an analysis of a sample of pure white gypsum collected near Cascade Springs:[1]

[1] By Mr. George Steiger.

| | |
|---|---|
| $SiO_2$ | 0.10 |
| $Al_2O_3$ | 0.12 |
| CaO | 32.44 |
| MgO | 0.33 |
| $H_2O$ | 20.80 |
| $SO_3$ | 45.45 |
| $CO_2$ | 0.85 |
| | 100.09 |

Gypsum also occurs, forming interlacing networks of veins in the red sediments. The veins can be traced directly to adjacent beds of gypsum, and range from paper thinness to two or three inches. Frequently vein structure, crystals oriented perpendicular to the walls, occurs and sometimes two periods of formation of crystals are evident.

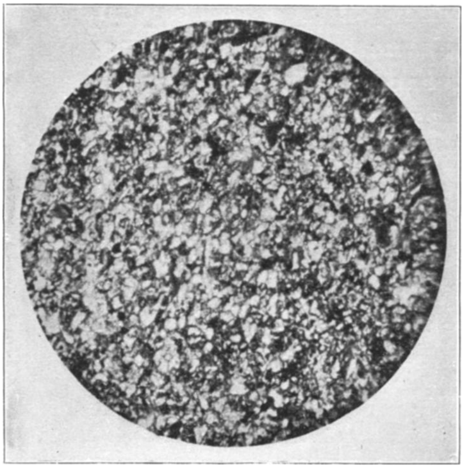
The red beds rest on the underlying purple limestone everywhere conformably. There is no indication of a period of exposure of the limestone to subaërial influences, but there is a sharp contrast in the character of the sediments. Massive limestone generally is followed abruptly by red shales; though in places—sections IV, V, and XVIII—gypsum immediately overlies the limestone.

In contrast to the uniformity of the lower contact, the transition from the upper red beds to the Jurassic is variable. The change does not occur in the red beds themselves, but rather marks the beginning of the Jurassic. The upper contact is locally an undulating, gently eroded surface; frequently, however, the contact is plane and apparently conformable. The upper contact is occasionally marked by pebbles of quartz varying in size from pin-heads to peas (section XVII). In one instance (section XIX) gypsum was found at the extreme top of the formation. The most pronounced change, though, is that of color. The uniform chocolate-brown shales of the upper Spearfish are succeeded by green shales or buff sandstones.

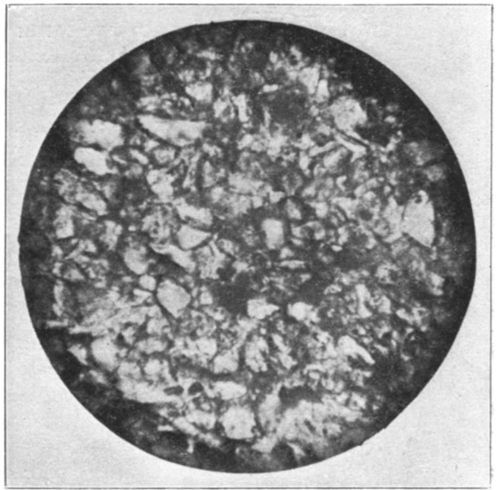
*Microscopic characters.*—Under the microscope the red shale is seen to be composed of minute white particles with irregular outlines coated by, and frequently including, an amorphous brown-red pigment. Quartz is the chief constituent, besides

which the white minerals are muscovite, calcite, magnesite, kaolin, gypsum, and feldspar. Some magnetite and ilmenite and occasional fragments of chlorite, are also present.

No systematic arrangement of the minerals occurs, the texture being characteristically sedimentary. The individuals are all minute; few are over $0.1^{mm}$ in cross-section, and the average is about $0.04^{mm}$.



Magnified 50 diameters. ×56



Magnified 136 diameters. ×136

Microphotographs of thin sections of the spearfish red beds.

The quartz grains vary in size from 0.03 to $0.06^{mm}$ in cross-section. The particles are angular to subangular, seldom well-rounded. Some of the contours are so irregular, though smooth, as to suggest corrosion. Many of the quartz grains are perfectly clear and transparent, while others contain inclusions. Slender prisms of rutile are included in a few of the quartz grains, while others contain fluid inclusions. These do not contain red pigment and probably are original minerals derived from the disintegration of the parent rocks. Other quartz grains contain numerous inclusions of the red pigment and doubtless this quartz is secondary, being formed in the presence of iron oxide.

Muscovite is present in small clear rods, averaging $0.1^{mm}$ long

by $0.006^{mm}$ wide. Sericite occurs sparingly in irregular patches averaging 0.06 or $0.07^{mm}$ in cross-section and consisting of minute fibrous plates.

Carbonates occur scattered throughout the slides in rhombs that average about $0.03^{mm}$ in cross-section and in small irregular particles.

The presence of kaolin is suggested under the microscope by dull white flakes of irregular outline and of low refraction and birefringence. Bits of red pigment are frequently included. And the presence of kaolin is probable from chemical tests. The color was discharged from a piece of red clay by digestion in hydrochloric acid. The resulting gray powder was examined under the microscope, and white flakes of low double refraction were isolated, excluding quartz as far as possible. These flakes reacted for aluminum and water before the blowpipe.

Feldspars are very sparingly present. Some clouded fragments seem to be decomposed orthoclase. A few irregular areas of microperthite of fibrous appearance are also present. And very rarely bits of decomposed plagioclase occur.

Gypsum and dolomite, or magnesite, were not determined under the microscope, but their presence is shown by chemical analysis.

Amorphous red pigment is prominent in the slides. It irregularly coats and spots the minerals, and is included in some. The inclusions seem to be restricted to quartz and kaolin. This pigment constitutes the chief interstitial substance. It does not occur in continuous vein-like impregnations, nor does it form bands or local accumulations.

Analysis shows that the red pigment is iron oxide and that probably it is completely anhydrous. Sample No. 54, in which the complete analysis shows 2.84 per cent. of combined water, was treated with hot hydrochloric acid until all of the iron was dissolved. The residue was found to contain 1.90 per cent. of combined water, leaving 0.94 per cent. available for the hydrous minerals which hydrochloric acid would attack. Gypsum, and possibly an iron hydrate, are the only ones that the acid would decompose. Calculating the amount of gypsum from the

amount of $SO_3$, it is found that 4.8 per cent. of the rock is gypsum. This requires 1 per cent. of water, which practically is the amount available. No water, therefore, is left for combi nation with the iron. It is true this calculation is but an approximation, but it appears evident that the red pigment is either anhydrous or nearly so.

*Chemical analysis.*—Two specimens of the Spearfish formation were analyzed by Mr. George Steiger, of the U. S. Geological Survey, with the following results:

| | Red Sandy Shale from East of Newcastle. No. 54. | Red Sandy Shale from East of Spearfish. No. 55. |
|---|---|---|
| $SiO_2$ | 56.20 | 58.32 |
| $TiO_2$ | 0.77 | 0.48 |
| $Al_2O_3$ | 11.50 | 8.59 |
| $Fe_2O_3$ | 3.64 | 2.04 |
| FeO | 0.65 | 0.18 |
| MnO | 0.10 | 0.07 |
| CaO | 5.83 | 8.45 |
| BaO | none | none |
| MgO | 4.23 | 3.65 |
| $K_2O$ | 3.74 | 2.71 |
| $Na_2O$ | 0.98 | 0.72 |
| Water 100 – | 1.61 | 0.52 |
| Water 100 + | 2.84 | 1.40 |
| $P_2O_5$ | 0.12 | 0.05 |
| $SO_3$ | 2.26 | 0.43 |
| $CO_2$ | 5.72 | 12.08 |
| Cl | trace | strong trace |
| | 100.19 | 99.69 |

The elements are so distributed that an exact determination of the relative abundance of the minerals in the rocks analyzed is impossible. Estimates based on the analyses and on the appearance under the microscope give the following approximate mineral composition of average red shale:

| | | |
|---|---|---|
| Quartz | 41 | per cent. |
| Muscovite | 20 | " |
| Kaolin | 10 | " |
| Calcite | 9 | " |
| Magnesite | 8 | " |
| Feldspars | 5 | " |
| Hematite | 3 | " |
| Gypsum | 2 | " |
| Magnetite, ilmenite, chlorite | 2 | " |
| | 100 | |

The analyses show traces of chlorine. Probably this is present as common salt, which, in spite of its solubility, may represent salt deposited in the red beds during their formation. No beds of rock salt have been found in the red beds of the Black hills, but a local accumulation is suggested by a salt spring in the red beds about three miles northeast of Cambria, Wyo. An analysis of this water by Mr. Steiger showed:

| | Grams per Liter. |
|---|---|
| $CaO$ | 1.960 |
| $MgO$ | .448 |
| $K_2O$ | none |
| $Na_2O$ | 27.334 |
| $SO_3$ | 3.556 |
| $Cl$ | 31.479 |
| $Br$ | none |
| $I$ | none |
| | 64.787 |
| Less $O=Cl$ | 7.094 |
| | 57.693 |

=51.582 grams of NaCl per liter.

DISCUSSION.

Red beds in general are well known to be colored by ferric hydrate or ferric oxide, but conditions that determine the formation and deposition of red pigment are various. Red beds have accumulated at different times and in different localities, under different conditions. This study was undertaken with the purpose of seeking evidence for the origin of the color of the red beds of the Black hills.

The history of these rocks is intimately connected with the history of the entire series of red beds of the central West, and a complete treatment of the subject is impossible without the accumulation of more facts, concerning the general geology of the Rocky mountains and adjacent regions, than are now known. Nevertheless the red beds of the Black hills constitute an isolated mass, and it is thought that an inquiry into the cause of their color, based on their description, will not be inappropriate.

*Theories for the origin of the color of red beds.*—One of the most obvious origins of red rocks is that they are formed by the dis-

integration and resedimentation of pre-existing red beds. This explanation, however, does not strike at the root of the matter, and in accounting for the color of such extensive masses of red beds as those in the western states is not applicable. For the rocks under consideration an explanation is demanded of the formation of original red beds. The following are the most important theories that have been advanced:

1. Water containing iron in solution percolating through rocks may have the iron precipitated as hydrate by contact with oxygen-bearing waters, or by other means. The hydrate thus formed subsequently may become dehydrated to the more stable red hydrate or to the anhydride. John W. Judd[1] in this way, explained the red color of the Northampton sands.

1 *a*. A variation of this method is the precipitation as iron carbonate of the iron contained in percolating waters by replacement of calcium carbonate with which the waters may come in contact. Oxidation may later convert the carbonate to the red iron oxide.[2] C. H. Smyth considers this one of the ways by which the red Clinton ores were formed.

2. Again, iron-bearing minerals in rocks on a land area may be decomposed by acidulated surface waters and the iron taken into solution as bicarbonate and transported to a body of water in which sediments are being deposited. Contact with air would convert the bicarbonate to ferric hydrate, which would be precipitated among the accumulating sediments.[3] Subsequent changes would dehydrate the iron precipitate to a stable red pigment. By this process bog iron ores are now accumulating. This explanation often has been appealed to in accounting for the color of red rocks. A. C. Ramsay[4] advocated such an origin for the color of the New Red sandstone. Also Henry Newton[5] applied this explanation, as his interpretation of the

[1] *Geological Magazine*, Vol. VI, p. 221.

[2] *Ibid.*, p. 487.

[3] Also some algæ have the power of precipitating ferric hydrate from certain iron solutions.--R. BRAUNS, *Chemische Mineralogie*, 1896, p. 383.

[4] *Quarterly Journal of the Geological Society*, Vol. XVII, p. 241.

[5] HENRY NEWTON, *Geology of the Black Hills of Dakota*, 1880, p. 138.

origin of the color of the red beds of the Black hills. In this way C. H. Smyth[1] accounts for the origin of some of the Clinton ores. And W. Spring[2] in his recent paper on the color of red beds accepts this theory and devotes his attention to details of how dehydration may take place after the iron has been precipitated as hydrate.

Another theory is that the color of red rocks may be caused by the sedimentation of a residual red soil. A. W. McKay[3] thus explained the color of the red sandstone of Nova Scotia. And I. C. Russell[4] has elaborated this theory and has applied it to the explanation of the color of the rocks of the Newark system.

3*a*. A variation in this process may occur when the iron in the soil, which furnishes the sediments of red beds, is not completely changed to the red ferric hydrate or to the anhydride previous to sedimentation. In such a case the soil would have a mottled color due to different stages of hydration of the disseminated iron compounds. Such mottled material may become uniformly red by dehydration of the disseminated iron subsequent to or during sedimentation.

J. D. Dana appealed to such a possibility in criticising Russell's widespread application of the theory of original deposition of red beds as such. Dana regarded conditions attending the consolidation of the rocks sufficient to cause the dehydration necessary to produce the uniform red. In the case of the rocks of the Newark system he considered the influence of the associated trap dykes, by virtue of their raising the temperature of interstitial water, potent to change to the anhydrous red oxide any limonite present about the individual rock particles.[5]

Dehydration may occur also during the process of sedimenta-

[1] C. H. SMYTH, *American Journal of Science*, Vol. XLIII (1892), p. 487.

[2] W. SPRING, *Recueil des travaux chimiques des Pays-Bas et de la Belgique*, Vol. XVII (1898), No. 2, p. 202.

[3] *Report British Assoc. Adv. Sci.*, Thirty-fifth Meeting (Birmingham, 1865), Part II, p. 67.

[4] *Bulletin 52, U. S. Geological Survey*, 1888.

[5] *American Journal of Science*, Vol. XXXIX (1890), p. 319.

tion. W. Spring[1] recently has shown that the presence of a salt in water produces on a hydrate an effect comparable to that of an elevation of temperature, and on this fact as a basis he would account for the color of red beds. Accepting the theory that red rocks are formed by the precipitation from solution of ferric hydrate about the individual particles of a deposit in an area of sedimentation, Spring maintains that red beds were formed in estuaries or in saline lakes, where the presence of dissolved salts would bring about the dehydration of the precipitated ferric hydrate necessary to produce the red pigment. The dehydrating effect of salt water is an important contribution, but whether the pigment of red beds was deposited from solution or as mechanical detritus is an independent subject, and one which must be settled by the study of any particular red formation.

*Application of theories.*—Let us now examine the evidence presented by the red beds of the Black hills, in connection with the requirements of these theories.

The first, providing for the deposition of the coloring matter by precipitation from percolating water subsequent to the formation of the rock, clearly is inapplicable. There are no available rocks which could supply sufficient iron in solution, neither is there any apparent reason why the pigment, if thus deposited, was limited to its present extent. Moreover, the uniform distribution of the coloring matter throughout the red beds in minute quantity, instead of in irregular or local accumulations, is difficult to explain by this theory. The coating of iron oxide about grains of quartz offers no suggestion that the pigment is a product of replacement. And the great extent of these red rocks seems to preclude the subsequent origin of the pigment.

The second theory—that the coating of pigment about the rock particles was precipitated from solution during sedimentation—is that which has been most generally appealed to in explanation of the color of red beds. The facts that such an

[1] W. Spring, *Recueil des travaux chimiques des Pays-Bas et de la Belgique*, Vol. XVII, No. 2 (1898), p. 202.

explanation accounts for the red coating of the individual particles, and that it is difficult to disprove, are in its favor. Nevertheless, while it cannot be maintained that no ferric hydrate was precipitated from solution among the accumulating sediments under consideration, yet the evidence is that such was not the principal source of the pigment.

It will be shown presently that the climate during the sedimentation of the red beds probably was arid. Under such conditions vegetation would be scant, and surface waters would not be heavily charged with solvents. Conditions then were not specially favorable for rock decay, nor for the transportation of iron in solution to the area of deposition during red-bed time. Besides, if such were the origin of the pigment, local accumulations of it would be expected as in the case of those Clinton ores for which such an origin is accepted, and in the case of bog ores now forming. On the contrary, in none of the rocks examined microscopically does the thickness of the pigment amount to half a millimeter, and usually it is much thinner. The exact equilibrium required for the chemical precipitation of ferric hydrate to be just sufficient to coat each sedimentary particle, no more nor less, is extremely improbable.

Then there is the theory, emphasized by Russell, that red beds may be formed by the sedimentation of a residual red soil, and the evidence seems to be in favor of such an origin for the red beds of the Black hills.

It is a familiar fact that under suitable conditions rocks which contain iron-bearing minerals weather to a red clay. In the process of rock disintegration and decomposition the iron-bearing minerals alter easily. Ferrous iron—in biotite, hornblende, and pyroxene, for example—becomes oxidized and hydrated to limonite, which dehydrates and passes through stages corresponding to göthite and turgite, to the stable red hematite.[1] A late stage of residual soil, from a variety of parent rocks, consists of the stable minerals quartz, kaolin, and muscovite, traces of original rock constituents in various stages

[1] W. O. CROSBY, *American Geologist*, Vol. VIII (1891), p. 72; G. P. MERRILL, *Rocks, Rock Weathering and Soils*, 1897, p. 299.

of alteration, and red pigment indiscriminately distributed among the individual soil particles. Instances of residual red soils are numerous. Notable occurrences are: the soils of the Piedmont plateau of the southern Appalachians, the terra rossa of Europe, the laterite of India and the red soil of the valley of the Amazon.

Streams coursing over lands mantled with residual red soil transport it to areas of deposition, and thus tend to cause the sedimentation of red rocks. In many instances, however, in regions where red soils are abundant the red material washed from the land turns brown, and often greenish or bluish, before final deposition among accumulating sediments. For instance, in the Piedmont plateau region of the southern Appalachians red detritus in the streams generally becomes decolorized to the more somber tints of ferrous compounds, because of the deoxidizing influence of abundant decomposing organic matter in the water. But such destruction of the red color of detrital material so as to prevent the actual deposition and accumulation of red sediment is not universal. Thus enough of the red material brought down by the Amazon escapes deoxidation, so that vast deposits of red rocks are now accumulating along the coast of Brazil.[1] And it is probable that under more favorable conditions red rocks would accumulate more generally than now occurs. Such conditions would be the greater prevalence of areas covered with residual red soil and the absence of much organic matter in the waters concerned with the transportation and deposition of the red material.

In the case of the red beds of the Black hills it seems probable that unusually favorable conditions did exist both for the formation of a parent residual soil and for its accumulation as red sediment.

The geography of the Rocky mountain and adjacent regions in red-bed time[2] remains to be worked out. Still it is generally

[1] JOHN MURRAY, *Challenger, Reports Deep Sea Deposits*, 1891, p. 234.

[2] The age of the red beds of the Black hills, considered as an entire series, is not satisfactorily known, because no fossils have been found in the upper and lower formations. The intermediate limestone, however, carries fossils which indicate it to be Permian, but whether the lower red beds are in part Carboniferous or whether the upper are partly Triassic there is no direct evidence.

agreed that during the accumulation of the red beds of the central West a shallow mediterranean sea, whose outlines are very imperfectly known, existed west of the Mississippi and east of the great basin extending northward from Texas almost into Canada. In the midst of this sea the Rocky mountain province formed a group of islands.[1] Stratigraphic evidence renders it probable that different conditions prevailed simultaneously in different parts of the sea and that different conditions prevailed at different times in the same area. But insufficient facts have been accumulated to warrant a detailed statement of conditions that existed during the deposition of the red beds.

The Black hills area was covered by this body of water. The red beds there everywhere succeed the underlying Carboniferous rocks, with no signs of an interval of erosion. There is no evidence of thinning as the red beds approach the center of the hills, nor of off-shore conditions. Moreover, the dips carry these rocks over the highest points of the hills. The Black hills did not supply the sediments under consideration.

For the source of these red beds we must look to the land masses that were contiguous to the Black hills in red-bed times. These were an area of Algonkian rocks to the north and northeast, the lately uplifted Carboniferous limestone to the southeast, and the Rocky mountain area to the southwest and west.

That the limestone furnished sediments to the accumulating red beds in the Black hills cannot be denied, for the relatively insoluble constituents of limestone often form a residual red clay. Yet it is not likely that this was a prominent source. Of the areas named probably the limestone was the farthest away from the Black hills. Furthermore, the abundant quartz and mica in the red beds, and the presence of feldspar, magnetite, and ilmenite, point to a source from crystalline rocks rather than from limestone.

The extent of the Algonkian rock area is very indefinitely known, and it is doubtful whether this area contributed to the red beds of the Black hills. In this general region there was an

[1] S. F. EMMONS, *Bull. Geol. Soc. Amer.*, Vol. I (1890), p. 245; R. C. HILLS, *Proc. Colorado Scientific Soc.*, Vol. III (1888–90), p. 362.

extensive land area which may have been such from Cambrian down to Cretaceous time, but during red-bed deposition the respective limits of water and land are unknown. At Sioux Falls, S. D., there is an exposure of the Algonkian, the Sioux quartzite, which artesian-well borings show to have a considerable extent below the Cretaceous. The Sioux quartzite is a red rock which could have furnished red sediments. Microscopic study, however, renders it unlikely that this formation contributed to any considerable extent to the Spearfish formation. A characteristic feature of the Sioux quartzite is that it is composed of rounded quartz grains, the outlines of which are delicately traced by circlets of iron oxide imbedded in a matrix of interstitial silica crystallized in conformity with the nucleal quartz.[1] The red beds under consideration show no trace of this siliceous rim, which would be expected were the rocks derived from the Sioux quartzite.

The Rocky mountain region, however, was an available source of sediments for the red beds of the Black hills. During red-bed time this area was flanked by the deposition of red sediments whose constituents can be directly traced to such an origin.[2] And although the eastward extent of these red beds toward the Black hills is now deeply hidden by overlying rocks, so that actual stratigraphic connection has not been traced between the red beds contiguous to the Rocky mountains and those of the Black hills, yet such connection seems probable. Wells that have been put down deep enough east of the Rockies invariably have penetrated these red rocks. And the diminution in thickness of red-bed sediments from about three thousand feet adjacent to the mountains to five hundred feet in the Black hills, with an accompanying decrease in fineness of materials strongly suggests that the red beds of the Black hills are continuous with those of the eastern slope of the Rocky mountains.

The unusually favorable conditions, referred to above, for the

[1] S. W. BEYER, *Iowa Geol.*, Vol. VI (1897), p. 102.

[2] A. C. SPENCER, "Geology of the Rico Mountains," *Twenty-first Annual Report, U. S. Geological Survey* (1900), Part II, p. 68; G. K. GILBERT, *Pueblo Folio, U. S. Geological Survey*, 1897.

accumulation of a parent residual red soil and for its deposition as red sediment in the Black hills area were climatic.

It is generally believed that the Carboniferous climate in the present temperate zone was warm and moist. Under such influences the rocks of the Rocky mountain region, which general region is believed to have been land since the Cambrian,[1] were subjected to very favorable conditions for extensive decomposition and for the formation of a mantle of residual red soil. And because of the considerable decomposition the continued formation of red soil coincident with the removal of surface accumulations to supply red-bed sediments was facilitated.

It has been noted, however, that many regions which are now covered with residual red soil do not contribute red material to areas of sedimentation, because the red color is destroyed by deoxidation before or during deposition. But in the case of the red beds under consideration there is reason to believe that this deoxidizing influence was unimportant.

A relatively arid climate in many regions is known to have followed the warm and moist Carboniferous. That this was true in the red-bed region of the central West is testified to by the presence of beds of rock salt and gypsum. In the Black hills, though no beds of salt have been found in the red beds, yet the salt spring near Cambria suggests a local deposit; and interbedded gypsum is abundant.

There can be little doubt that the gypsum of these red beds was accumulated by precipitation from concentrated water containing calcium sulphate in solution. The "bar theory" of Ochsenius[2] clears the difficulty of conceiving how thick beds of chemically precipitated matter can be accumulated; and all the field relations of the gypsum point to such an origin. There is no indication that the gypsum is the result of the action of sulphuric acid on limestone. The bedded character of the gypsum interstratified with detrital sediments, the general occurrence of the gypsum in lenses, the frequent presence of layers of red sand and clay in beds of impure gypsum and of thin layers of

[1] EMMONS AND HILLS, *op. cit.*

[2] *Zeitschrift für praktische Geologie*, 1893, p. 189.

gypsum among the red sediments, besides the presence of gypsum disseminated throughout the red sediments, as shown by the rock analyses, lead to the conclusion that the gypsum was deposited as a chemical precipitate contemporaneously with the detrital sediments. Such an origin demands a somewhat arid climate.[1]

Now, an arid climate, sufficient to cause the precipitation of beds of gypsum tends to cause the preservation of the color of red sediments. Being unfavorable for the existence of abundant life in inland waters, such a climate minimizes the prevalence of deoxidizing influences incident to the presence of organisms. In this connection the general absence of fossils in the red beds is noteworthy.

With such favorable conditions for the accumulation of a red soil and for its deposition as the red beds of the Black hills let us look now for direct evidence bearing on the origin of the color furnished by the composition of the rocks under consideration.

The chemical composition of the red beds of the Black hills is essentially that of a residual red clay, notwithstanding the abundance of carbonates and sulphates. These unusual constituents were not of detrital origin, but were caused by conditions of sedimentation.

The gypsum already has been referred to, and considering the general paucity of life in the water in which these red beds were accumulated and the salinity of this water, the calcium and magnesium carbonates, which are disseminated throughout the red beds, appear to have been formed as chemical precipitates instead of having had a more direct organic origin. The presence of crystals of these carbonates means that they were deposited from solution. Their widespread and uniform dissemination, and the absence of veins and local accumulations, implies original deposition with the detrital sediments rather than subsequent introduction from percolating water. A secondary derivation from decomposition subsequent to sedimentation is

[1] The succession of a genial Carboniferous climate by post-Carboniferous arid conditions is emphasized by CHAMBERLIN, JOUR. GEOL., Vol. V, p. 678.

not borne out by the presence of associated, partly decomposed minerals.

Excluding these adventitious constituents, the analyses show the red beds of the Black hills to be composed essentially of silica, alumina, ferric oxide, potash, and water. These are characteristic components of residual soils, the corresponding mineralogical composition being the stable species, quartz, muscovite, kaolin, and the red pigment with occasional bits of decomposed feldspar.

The result of microscopic examination also shows the similarity of these red beds with residual red clay. Some of the quartz grains have intricate contours, as if etched by alkalies derived from decomposing feldspar. The disposition of the pigment as a coating to the individual rock particles is like that in residual red soils. And the inclusion of the red pigment in secondary quartz and kaolin is significant.

This inclusion implies the formation of the including minerals in the presence of the red pigment. It is not probable that these minerals were formed in the area of deposition when the sediments were accumulating so as to receive inclusions of iron precipitated from solution; nor is it a likely assumption that much decomposition took place subsequent to the formation of the red beds, and that the secondary minerals received inclusions of iron from percolating solutions. There is but little undecomposed material in the red beds, whereas considerable remains would be expected did alteration take place after sedimentation. The composition of the red beds is essentially of stable minerals, but some of the quartz and all the kaolin are products derived from decomposition. On the land area where the parent red soil of the red beds was accumulating, it is to be expected that in the intimate association of the constituents, iron oxide became included in the secondary minerals that were formed as decomposition products. Such inclusions are common in residual red clay in the District of Columbia.

It seems probable therefore that the dominant factor in the production of the color of the red beds of the Black hills was a residual red soil on the land mass which supplied the sediments.

But inasmuch as favorable conditions for dehydration existed in the area of deposition, it must not be asserted that the color of the red beds of the Black hills was entirely formed in the parent soil, and that none of the color was formed during sedimentation.

W. O. Crosby has called attention to the effect of exposure of iron-bearing sediments in shallow-water areas of deposition upon the production of red pigment.[1] This action depends on the dehydration of hydrated iron compounds and is a further operation of the influences which have been emphasized as the effective cause in the production of a residual red soil.

Another factor in the production of red pigment from hydrated iron compounds is the dehydrating effect of salt water discovered by W. Spring.[2] Because the red beds of the Black hills were deposited in concentrated waters, this influence operated and may have been important.

The presumption is, however, under the favorable climatic conditions and from analogy with the homogeneous red tint of many present residual red soils, that before the soil particles were actually deposited they had become completely red. But the possibility of these two causes having acted must not be forgotten. And, too, the fact must be borne in mind that the dehydration of ferric hydrates tends to go on under ordinary conditions without any unusual cause.[3] So that it is unnecessary to assume the action of further dehydrating agencies than those operating on the land which supplied the residual soil.

Whether a change in the pigment occurred subsequent to deposition, as suggested by Dana,[4] should be considered, inasmuch as the Black hills have been subjected to igneous intrusions. There are, however, in the central west province, red beds—similar to those in the Black hills and apparently genetically connected with them—which are not associated with

[1] W. O. CROSBY, *Proc. Boston Soc. Nat. Hist.*, Vol. XXIII (1888), p. 509.

[2] *Op. cit.*

[3] This has been repeatedly demonstrated by experiment: WITTSTEIN, *Vierteljahresschrift für Pharmacie*, Vol. I (1852), p. 275; DAVIES, *Jour. Chem. Soc. of London*, Vol. XIX (1866), p. 69; VAN BEMMELN, *Recueil des travaux chimiques des Pays-Bas et de la Belgique*, Vol. VII (1888), p. 106.

[4] *Op. cit.*

igneous rocks. Moreover, if the igneous rocks of the Black hills exerted a dehydrating influence sufficient to change the red beds from a possibly mottled previous condition to their present uniform color, such influence surely would have dehydrated the varicolored iron pigments in the underlying Carboniferous sandstone. This, however, did not occur, and the suggestion of Dana is not applicable in the Black hills.

*Green variations.*—The occurrence of green variations in red beds has caused some[1] discussion. In the case of true green beds among sediments derived in general from red soils, it seems likely that such green beds were either deposited from a locally different source than the red material, or that they represent red sediments which were deoxidized in the area of deposition. But small green spots and streaks, which constitute the general occurrence of green material in the Spearfish formation, can best be explained by considering them to have been developed subsequent to deposition.

These variations can be accounted for by the influence of occasional bits of organic matter present in the sediments. Such decomposing organisms reduced the ferric iron of the red pigment to a soluble form that was removed in solution, and green spots and streaks remained. In spite of the lack of more evidence of organic remains in the red beds, these green variations are difficult to explain in any other way. The irregular distribution of the green patches, their occasionally following cracks in the rocks, and their similarity in composition to the adjacent red clay, from which they differ only in containing less iron, point to this explanation.

GEORGE B. RICHARDSON.

[1] GEORGE MAW, *Quarterly Journal Geological Society of London*, Vol. XXIV, p. 351; T. N. DALE AND W. T. HILDEBRAND, *Nineteenth Annual Report United States Geological Survey*, Part III, p. 255.